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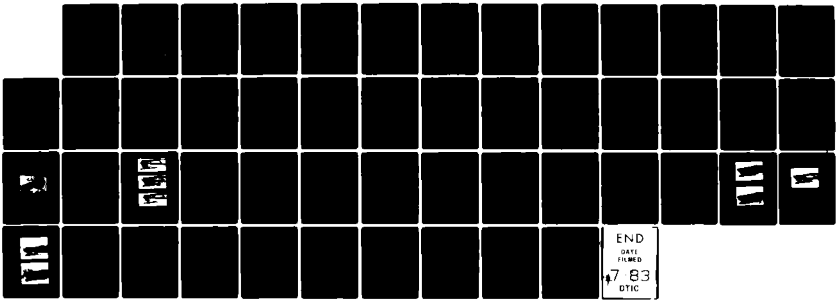

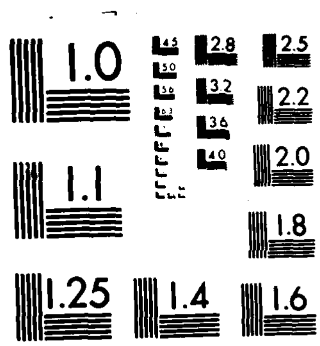

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RELATIVE MOTION AND DECK WETNESS OF THE SL-7 CONTAINERSHIP

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

(12)

RELATIVE MOTION AND DECK WETNESS INVESTIGATION OF THE SL-7 CONTAINERSHIP

by

JOHN F. O'DEA

SHIP PERFORMANCE DEPARTMENT REPORT

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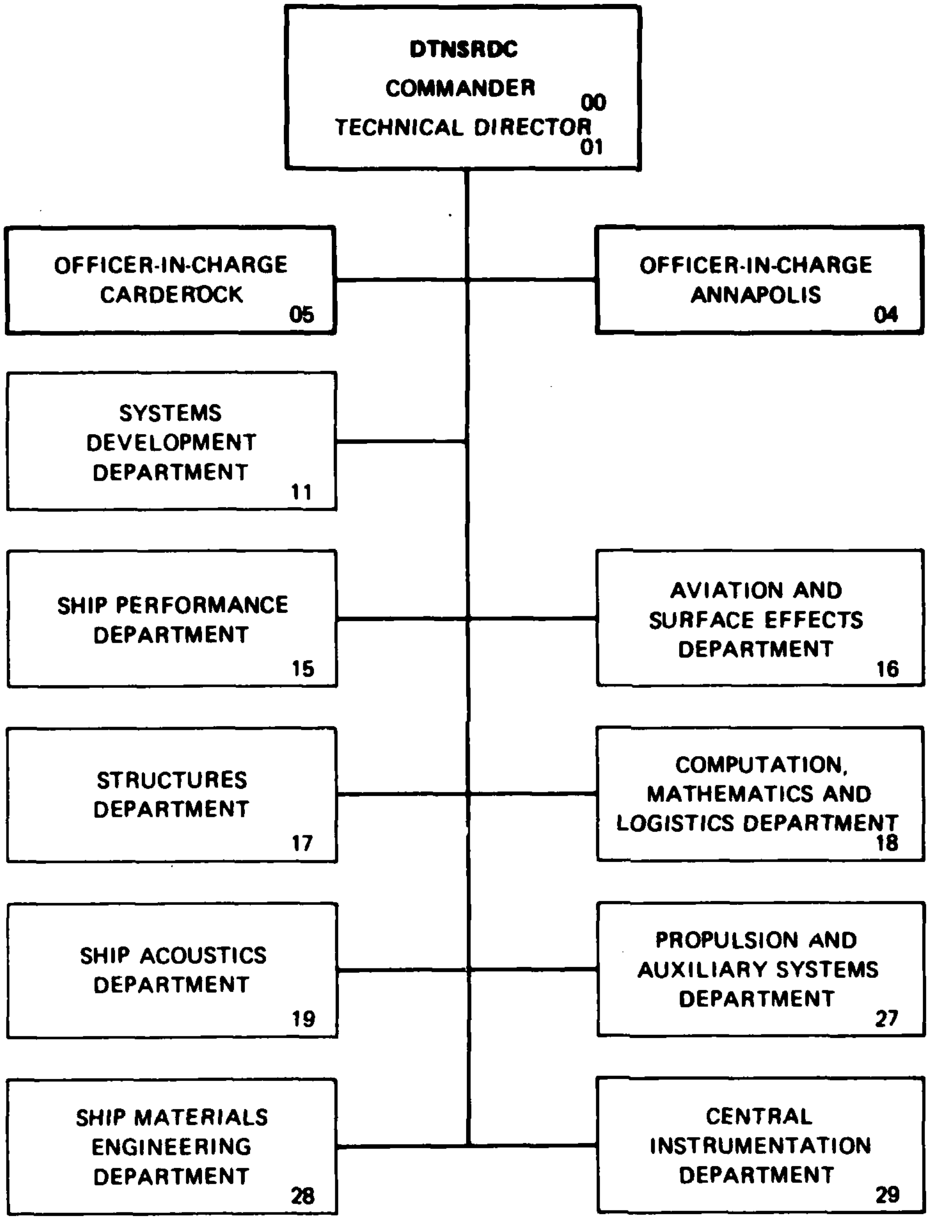

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A model of an SL-7 containership was towed in calm water and in waves to determine its relative motion and deck wetness characteristics. Several relative motion components were measured, including wave diffraction and mean shifts in waves which are not currently included in predictions of relative motions. It was also found that the above - water flare of the bow was very effective in reducing deck wetness.

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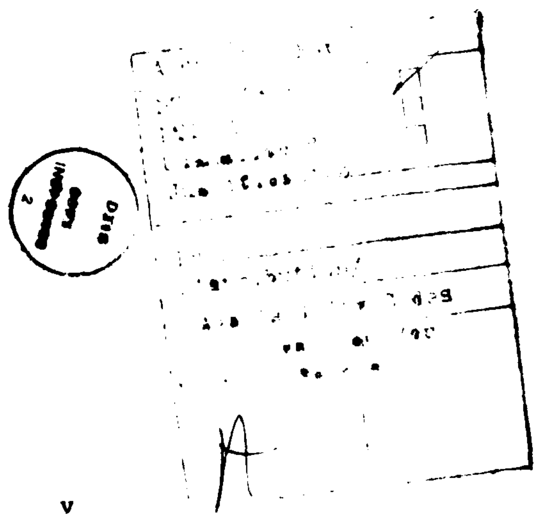

NOTATION

F_n	Froude number
$(\zeta_w)_{1/3}$	Significant wave height
k	wave number $(2\pi/\lambda)$
L	Ship length
LCG	Longitudinal center of gravity
ε_3	Phase angle of heave relative to wave
ε_4	Phase angle of roll relative to wave
ε_5	Phase angle of pitch relative to wave
ζ_A	Incident wave amplitude
ζ_O	Amplitude of Incident plus diffracted wave
λ	Wave length
ξ_3	Amplitude of heave motion
ξ_4	Amplitude of roll motion
ξ_5	Amplitude of pitch motion
ξ_R	Amplitude of relative motion

ABSTRACT

A model of an SL-7 containership was towed in calm water and in waves to determine its relative motion and deck wetness characteristics. Several relative motion components were measured, including wave diffraction and mean shifts in waves which are not currently included in predictions of relative motions. It was also found that the above - water flare of the bow was very effective in reducing deck wetness.

ADMINISTRATIVE INFORMATION

This investigation was jointly funded by the U.S. Coast Guard Commercial Vessel Safety Program under MIPR Z 70099-1-01832, and the U.S. Navy Ships, Subs and Boats Exploratory Development Program and the General Hydromechanics Research Program both of which are administered by the Naval Sea Systems Command. The work was carried out at the David W. Taylor Naval Ship R&D Center (DTNSRDC) and identified as Work Unit Numbers 1568-036, 1507-101 and 1568-102.

Selected data have already been published, see reference 1*, but this document provides comprehensive details of the investigation.

INTRODUCTION

Relative vertical motion between a ship hull and the water surface can significantly affect operability in a seaway. Excessive relative motion may cause deck wetness or propeller racing, and combined with large relative velocity, may cause bottom slamming. In order to gain a better understanding of the physical phenomena involved, particularly

*References can be found on page 17

regarding deck wetness, a model experiment program has been undertaken. The program had four main phases. The first involved measurement of the various factors affecting the mean freeboard in calm water, i.e. sinkage, trim, and bow wave profile. The second involved measurement of transfer functions of absolute and relative motions in regular waves. The third involved an investigation of relative motion and deck wetness in random waves. Finally, because very little deck wetness was observed even in severe random waves, a fourth set of experiments was carried out with the model trimmed down by the bow in order to obtain data for which relative motion could be correlated with the level of water on deck.

THE EXPERIMENTS

The hull form chosen for the investigation was that of the SL-7 class of containership. A body plan is shown in Figure 1 and a list of principal dimensions is given in Table 1. More detailed information on the ship is given by Boylston et al[2]. A model (Number 5409) of the SL-7 was constructed of wood to a scale ratio of 60:1. It was attached to the towing carriage of the Maneuvering and Seakeeping (MASK) Basin at DTNSRDC by means of a heave staff and roll-pitch gimbal, and was restrained in surge, sway and yaw. Heave, pitch and roll were measured by means of potentiometers. Relative motion probes were of the resistance wire type, and consisted of pairs of metal strips embedded in an epoxy substrate. The relative elevation of water on the hull caused a variation

in electrical resistance between each pair of wires, and this resistance was converted to a reading of vertical relative motion. Probes for measuring the depth of water on deck were mounted on centerline at stations 0, 1 and 2, and in addition two probes were mounted off the centerline port and starboard at station 1, at a distance equal to 15 feet (4.57m) full scale. These deck wetness probes were also of the resistance type. Both the relative motion and deck wetness probes are shown in Figure 2.

Experiments were run in head waves (wave heading = 180°) and bow waves (waves approaching from port bow, heading = 225°). Incident wave elevation was measured with an ultrasonic transducer mounted rigidly to the towing carriage approximately one-half ship length in front of the bow. For measuring the diffracted wave component of relative motion, the model was rigidly locked to the carriage.

All measurements were digitized and analyzed by a carriage-mounted computer. Analysis of the first and second phases of experiments consisted of calculating mean values and the first harmonics of the various oscillatory quantities. Analysis of the third phase (in random waves) consisted of a statistical analysis of peaks and visual observation of deck wetness by means of a color video system. The final phase of the experiments was analyzed by detailed examination of the time history records.

RESULTS

Experimental results for the four series of experiments will be

discussed in separate sections. Unless otherwise noted, all dimensional results will be given for the full scale SL-7 ship.

EXPERIMENTS IN CALM WATER

The model was towed in calm water at three speeds corresponding to ship speeds of 10, 20 and 30 knots (Froude number = 0.10, 0.20 and 0.30). The model was towed two ways: free to trim, and fixed at zero trim. The sinkage and trim measurements for these speeds are shown in Figure 3. Photographs of the bow wave profiles in the free-to-trim condition are shown in Figure 4 and the measured bow wave profiles, as recorded by the relative motion probes at stations 0, 1, 2 and 3, are shown in Figure 5. It can be seen that the ship undergoes essentially level sinkage over the speed range tested, since the maximum trim angle is not much greater than the resolution of the pitch measurements transducer. Measurements of the change in level at bow and stern confirmed this, indicating a very small bow up trim. It should also be noted that the difference in the measured bow wave profiles between the fixed and free trim experiments is not completely explained by the amount of trim measured.

One unusual aspect of the bow wave profile is a thin sheet of water which curls up around the stem and as far back as station 1 at a speed of 30 knots (see Figure 4(c)). This produces an unconventional wave profile along the side of the hull, with the maximum elevation at the extreme forward end of the waterline. This phenomenon is apparently

caused by a combination of the steady sinkage at the bow due to forward speed and the rounded waterline endings above the design waterline. As will be shown in the experimental results below, this wave profile can be enhanced when pitching down in waves and can have a significant effect on the amount of spray generated. It is not known whether this wave profile appears on the full-scale ship, but the measured elevation at 30 knots at station 0 is in close agreement with the value reported by Boylston et al[2].

EXPERIMENTS IN REGULAR WAVES

The model was towed in regular waves at speeds of 10 and 30 knots, and headings of 180 degrees (head waves) and 225 degrees (bow waves, incident on the port bow). The waves were of moderate steepness, with a nominal height-to-length ratio of 1:50. Measured values of incident wave height, heave, pitch, roll (in bow waves) and relative bow motion were digitized and harmonically analyzed. The first harmonics of the quantities of interest were used to calculate transfer functions.

The transfer functions of heave, pitch and roll are presented in nondimensional form in Figures 6-8. The magnitude of heave has been normalized by wave amplitude while the magnitude of pitch has been normalized by wave slope ($k\zeta_A$). Phase angles are defined as phase leads with respect to maximum positive incident wave elevation at the center of gravity of the ship, where positive heave, pitch and roll are defined as upwards,

bow down, and starboard side down, respectively. Data were obtained at approximately twelve wave lengths ranging from one-half to three times the ship length, and curves were faired through these points for clarity in presentation.

Relative motion transfer function magnitudes are shown in Figures 9-11. The magnitudes have been normalized by incident wave amplitude. As shown, relative motions are considerably increased at the higher speed. The effect of changing heading from head to bow waves is to shift the peak responses to shorter wavelengths, and to increase the magnitudes on the incident wave (weather) side relative to the lee side. The latter effect is not associated with rolling motion, since there is little roll at such short wavelengths, but is caused by the diffraction effect of the hull on the waves. This effect was confirmed in a separate set of experiments, explained below. The maximum nondimensional relative motion was measured at station 1 at 30 knots (Fn=0.3) in bow seas (weather side), where the relative motion was greater than five times the incident wave amplitude.

One component of relative motion which has received little attention is the distortion of the incident wave, caused by diffraction around the hull. To investigate the diffraction effect, a series of experiments was done in which the model was rigidly attached to the carriage and towed in waves. The resulting effects on relative motion are shown

in Figure 12, for Fn=0.3, where again the amplitude of relative motion has been normalized by incident wave amplitude. If the hull had no disturbing effect on the incident waves, then the magnitude of the curves would have been 1.0 identically at all wavelengths, speeds and headings, because each probe would be measuring only the incident waves. The data thus show that the hull does have a significant diffraction effect. In head waves, the effect ranges from negligible at station 0 at Fn=0.3, to as much as 40-50% over the incident wave amplitude in short waves at stations 1-3. It is significant that this effect remains quite large over the entire wavelength range. In oblique (bow) waves, the effect of the hull is to partially reflect the incident wave, which further increases the relative motion on the incident wave (port) side of the hull, while decreasing it on the lee side. This effect is strongest in short waves, where the relative motion on the incident side may be double the incident wave amplitude, while the relative motion on the lee side may be as low as 85% of the incident wave amplitude. The diffraction effects at lower speeds are qualitatively similar, although not as pronounced.

A more complete theoretical and experimental examination of the various components contributing to the relative motion transfer functions is given by Lee et al[1], who found that noticeable discrepancies still exist between strip theory predictions of relative motion and experimental measurements. Part of this lies in the prediction of the absolute rigid body motions, and part in the prediction of the phases of radiated and

diffracted waves. Furthermore, it does not appear that strip theory is adequate for predicting the magnitude of the diffraction effect at longer wave lengths.

One final aspect of relative motion which was examined was the effect of motions in waves on the mean values of relative motions. It has usually been assumed in the past that the oscillatory component of relative motions in waves could be superimposed on the mean shifts caused by sinkage, trim and bow wave profile in calm water. However, these experiments do not confirm this. When the mean values of absolute and relative motions were carefully calculated by averaging over an integer number of encounter periods, it was found that heave, pitch and relative motions all had mean shifts in waves, in addition to the mean shifts in calm water. These extra shifts, while not large, vary with the wavelength-to-shiplength ratio and are most noticeable at high speeds. Examples of these shifts are shown in Figure 13. The results are shown in dimensional units (full-scale) for waves of 1:50 nominal height-to-length ratio. It is not known how these results would vary with wave steepness, but the fact that there is a shift in the mean implies there is a nonlinear mechanism involved.

EXPERIMENTS IN RANDOM WAVES

A series of experiments were performed in random waves to determine the deck wetness characteristics of the SL-7. The wavemakers were pro-

grammed to produce random waves corresponding to Sea State 5, 6 and 7 with nominal significant wave heights of 10, 15 and 25 feet (3.0, 4.6 and 7.6m) respectively. These experiments were largely unsuccessful in producing quantitative information on quantity, distribution and frequency of occurrence of water on deck since the bow flare of the hull served to effectively deflect water away from the deck. What water did reach the deck was almost entirely in the form of spray. Because it is known that spray does not scale properly in model experiments, the results reported below on wetness must generally be considered qualitative, and may not agree aith full scale observations.

The frequency of occurrence of wetness was estimated from studying video records of the experiments, and is shown in Table 2. As shown, the frequency of occurrence was quite small except at 30 knots in Sea State 7. It was also noticed from the video records that two different physical mechanisms, leading to large relative motion and deck wetness, were taking place. The first was the thin sheet of water curling around the rounded stem at higher speeds, which was also noticed in the calm water experiments. When relative motion became sufficiently large, this sheet was thrown up above the deck level where it broke into spray droplets and was carried aft onto the deck. This spray type wetness was not of sufficiently great density to trigger any response on the deck wetness probes. It was apparent only at higher relative velocity,

so spray generation did not appear often at 10 knots, became more frequent at 20 knots, and occurred perhaps every third encounter cycle at 30 knots Sea State 7. The second mechanism for generating large relative motion was the more commonly recognized combination of absolute motions and swell up caused by diffraction and hull generated (radiated) waves. These effects are more pronounced somewhat aft of the stem (around station 2 or 3) where the ship has larger cross-section. Furthermore, this physical mechanism is more likely to cause deck wetness further aft because of reduced freeboard associated with the sheer.

The second mechanism described above is a possible cause of deck wetness at all speeds, while the first depends strongly on speed. This is illustrated in the photographs of Figure 14. At each of the three speeds tested, it can be seen that at the instant these photographs were taken, the water surface was approaching the deck line near stations 2 and 3. At 10 knots, this was the dominant effect.

At 20 knots, the water level at station 3 appears to have exceeded the deck level, although the hull flare was effective in deflecting water away from the deck, and a curl of water now appears around the stem. At 30 knots, the curl water around the stem has just about reached the level of the bulwark and has begun to break up into spray droplets.

The design of the bow flare on this hull proved to be very effective in preventing green water from boarding over the stem or sides. Even at thirty knots in Sea State 7 bow seas, where spray-type wetness occurred

frequently, shipping of water to a measurable depth on deck was a rare event. This was true despite the fact that relative motion commonly exceeded the freeboard, as indicated by clipping of the relative motion signals. In fact, visual observation of this condition often indicated the simultaneous occurrence of a spray sheet coming directly over the bow and a wave elevation near stations 2 or 3 clearly above the level of the deck but being pushed away from the deck by the flared bow sections. Two photographs of this effect are shown in Figure 15. An extended series of experiments was run in the condition mentioned above (Sea State 7, 30 knots, Bow seas), corresponding to one and one-half hours full scale, and in this time period only one occurrence of measurable depth of water on deck occurred. The time traces of this occurrence are shown in Figure 16.

This occurrence of wetness happened when the modtel encountered a group of high waves, including two which measured 63 and 55 feet peak-to-trough. These two waves were, in fact, the largest and second largest in the entire wave record, which consisted of 823 encounter cycles. The time delay shown between these wave peaks and the occurrence of water on deck was caused by the wave measurement transducer being located considerably ahead of the bow.

Because so little deck wetness occurred in these experiments (except for spray), the experimental plan was modified to include a series of

experiments in which the model was trimmed heavily down by the bow in order to promote the occurrence of water on deck. The results of these experiments are described in the following section.

EXPERIMENTS IN BALLASTED CONDITION

The model was reballasted to a trimmed waterline which reduced the bow freeboard by about 40 percent. The trimmed waterline is shown as a dashed line in Figure 1. Because this was an extreme trim condition, runs were only made at slow speed (10 knots) in regular waves. Wavelength was varied until the most severe condition was reached, and at this particular wave length, the wave amplitude was gradually increased to obtain data which could provide a correlation between relative motion and depth of water on deck. Because of the slow towing speed, no spray generation occurred except that caused by water sloshing once it had covered the deck.

The regular wave experiments in the ballasted condition were performed over an abbreviated wavelength range, between one and two shiplengths. The pitch and heave transfer functions are illustrated in Figure 17. It was noticed that the most severe deck wetness appeared to occur at $\lambda/L = 1.5$, so at that wavelength, several more runs were made with gradually increased steepness. The maximum depth of water measured in each cycle at the various measurement points on the deck is shown, as a function of wave height ratio ($2\zeta_A/\lambda$) in Figure 18.

In order to more fully illustrate the deck wetness phenomenon, the time histories of the various measurements were analyzed for the most severe condition encountered, i.e., at $\lambda/L = 1.5$ and $2\zeta_A/\lambda = 0.05$.

The results are shown in Figures 19-20. In Figure 19, heave, pitch and incident wave elevation are shown for several cycles. The phase of the wave elevation trace has been adjusted so that it is correct at the center of gravity of the ship. The information in this Figure can be used to calculate the absolute vertical motion at any longitudinal position in the ship by a simple algebraic combination of heave and pitch. In addition, the relative vertical motion can be approximated at any location by subtracting the incident wave height (properly phase shifted for the specified location) from the absolute motion. This approximation may, of course, be in error since the effect of diffracted and radiated waves has been ignored. An example of such a calculation of relative motion is shown in the middle diagram of Figure 20 for station 0 on the SL-7, where this calculated relative motion is compared to the experimentally measured relative motion. The measured depth of water on deck is also shown in Figure 20. It can be seen that in this case, the calculated and measured relative motion at station 0 are in reasonable agreement until the point where the measurement is clipped as the bottom emerges or as the hull becomes completely submerged at this station. However, there is an indication that the measured relative motion in the bow down portion of a cycle would have been greater than

the probe had extended far enough above the deck. The maximum depth of water on deck at station 0 (centerline) is roughly the same as the amount by which the calculated relative motion exceeded the freeboard at that station.

The results for stations 1 and 2 are shown in Figure 21. It can be seen that the discrepancy between the calculated and measured relative motion is greater than at station 0, particularly in the bow down half of the cycle which affects deck wetness. Although the relative motion probe signals clip at the point where relative motion exceeds the freeboard, it is clear that if the probes were extended above the deck, they would register a value considerably greater than calculated from the incident wave and absolute (pitch and heave) motion. The amount by which the relative motion at the side of the hull exceeds the freeboard, is apparently much greater than the depth of water recorded on deck although this measurement may be affected by water draining off the deck. Furthermore, at station 1 where deck wetness probes were placed 15 feet (4.6m) either side of the centerline, as well as on centerline, the measured maximum depth of water on deck was greatest on centerline. Visual observation of the deck wetness indicated that water came on deck by flowing laterally in from the sides, rather than from the bow on centerline. Since this series of experiments was done only in head seas, the water came in symmetrically from both port and starboard,

and the increased depth at centerline was apparently caused by a flow stagnation phenomenon on centerline due to this symmetry.

CONCLUSIONS

The traditional method of predicting relative motion has been to calculate absolute vertical motion at a given point from the rigid body transfer functions of the hull, and to subtract this from the undisturbed incident wave at that point to provide an estimate of the relative motion transfer function. This transfer function is then used within the usual framework of seakeeping and random process theory to predict statistics of relative motion, which are compared to the freeboard in order to provide information on the frequency and severity of deck wetness. The experiments reported here show several areas in which the existing methods are inadequate. One result is that the hull can significantly distort the incident wave, and this diffraction effect should be included when calculating relative motion transfer functions. Experimental results also show the importance of including a number of effects which can change the mean freeboard from its static value. These include sinkage, trim and bow wave profile associated with forward speed, and an additional mean shift in waves. This last phenomenon is apparently caused by interference between the steady flow field caused by forward speed, and the oscillatory flow caused by the incident waves. Finally, it has been shown that relative motion itself is not adequate to predict either

the frequency of occurrence or severity of deck wetness. Even when relative motion at the side of the hull exceeds the deck level, the flare of the hull may serve to keep green water off the deck (while possibly increasing the severity of spray generation). When green water does come over the deck, the depth of water will be affected by the dynamics of the flow over the deck. Such effects are governed by non-linear hydrodynamics which are beyond the present state-of-the-art.

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2. Boylston, J.W., D.J. deKoff and J.J. Muntjewerf, "SL-7 Containership: Design, Construction and Operational Experience," SNAME Transactions, Vol. 82, pp. 427-478 (1974).

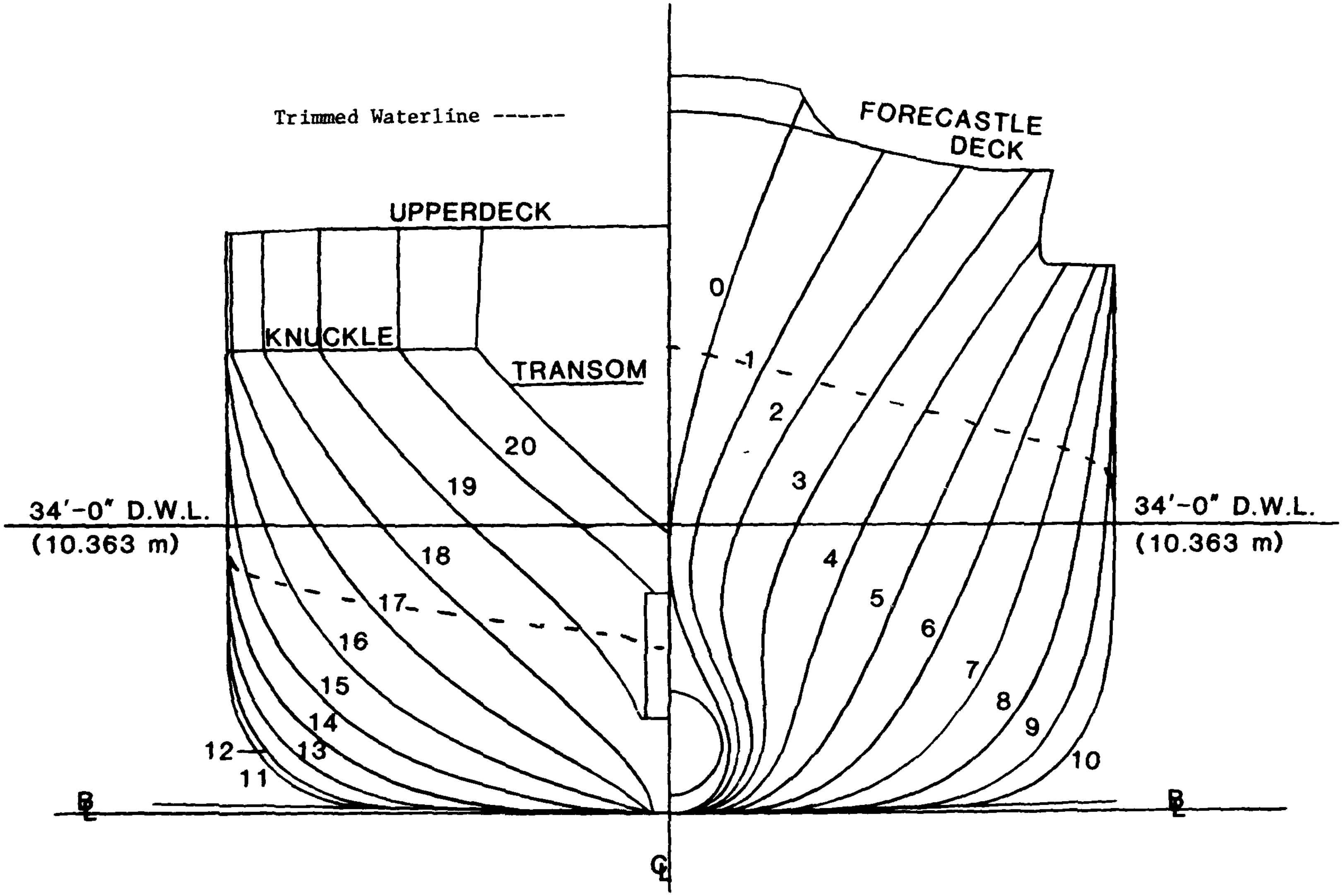


Figure 1 - Body Plan of SL-7 Containership

Figure 2 - Photograph of SL-7 Model, Showing Arrangement of
Relative Motion and Deck Wetness Probes

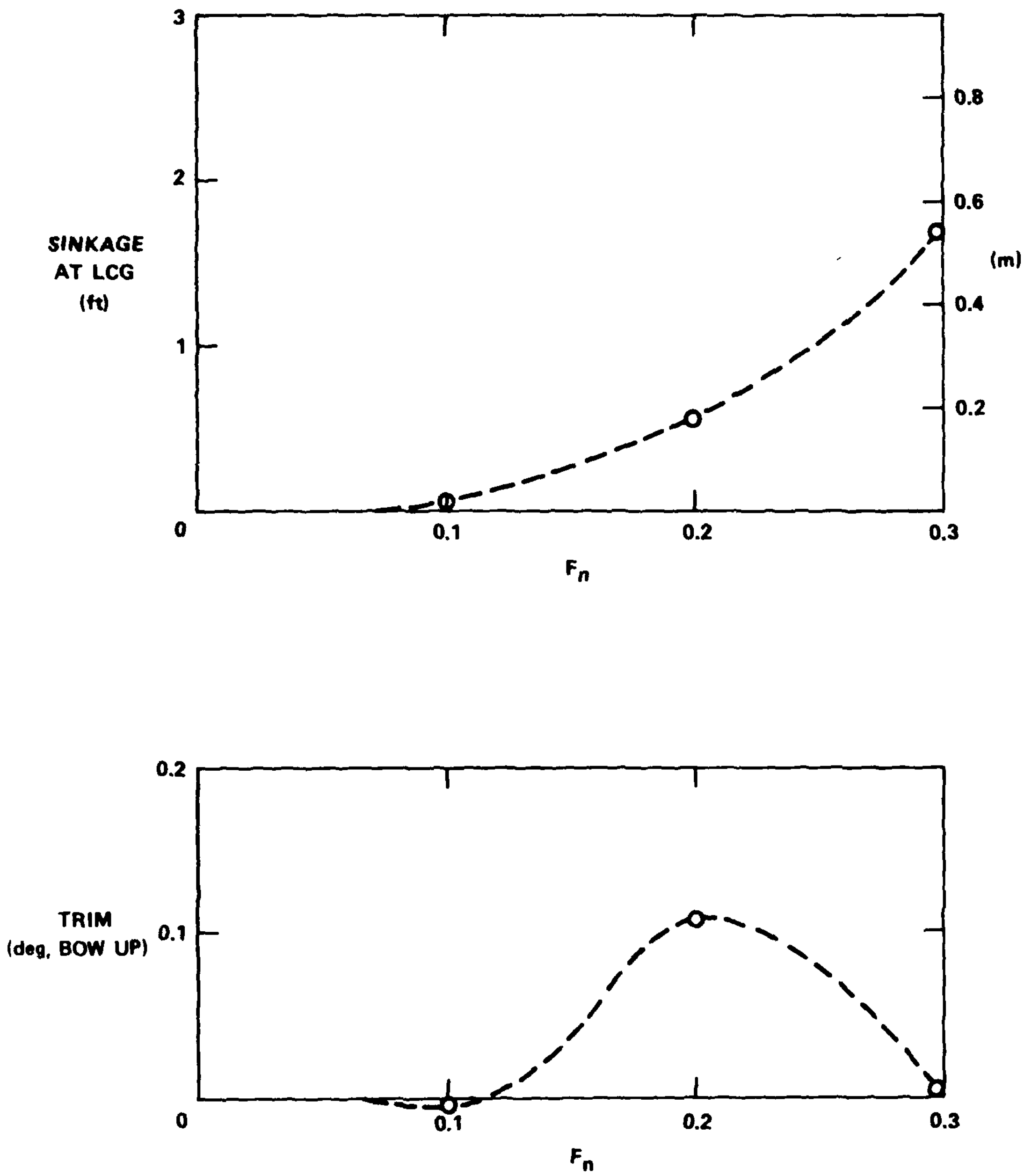
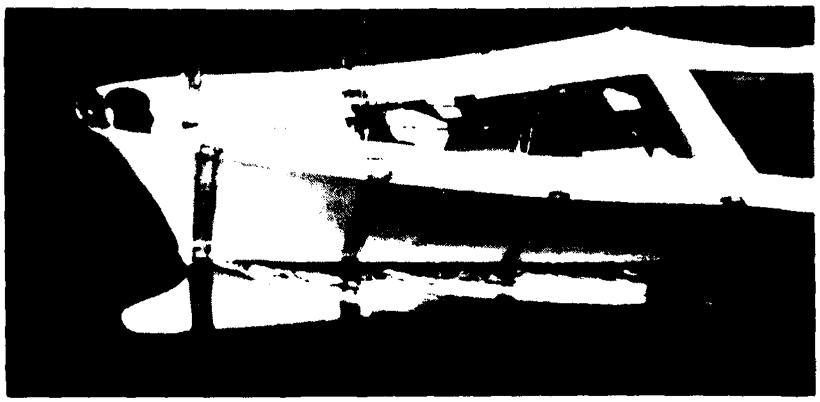


Figure 3 - Measurements of Sinkage and Trim in Calm Water

a) V = 10 Knots



b) V = 20 Knots

c) V = 30 Knots

Figure 4 - Photographs of Bow Wave Profile

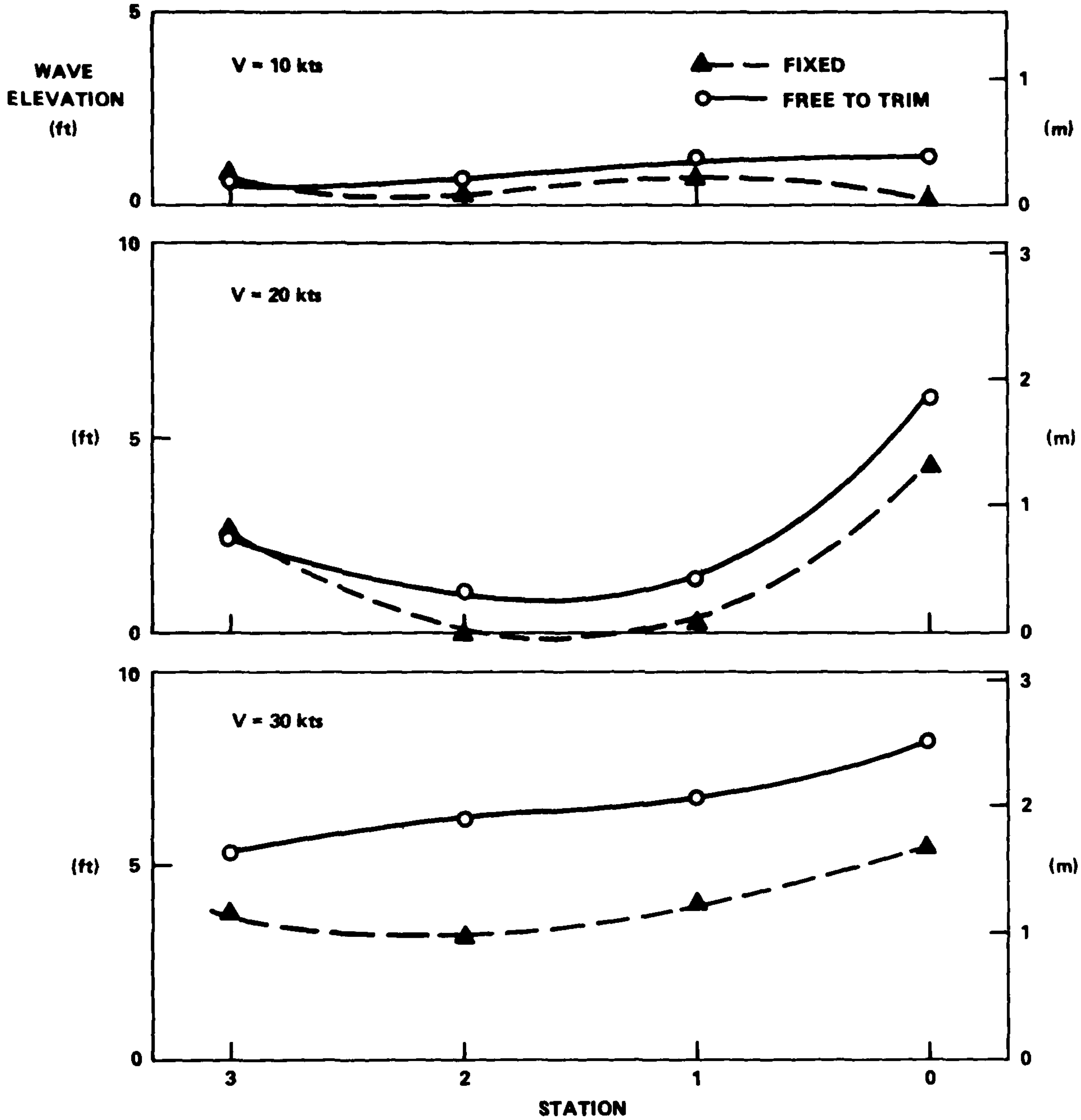


Figure 5 - Bow Wave in Calm Water as Measured by Relative Motion Probes

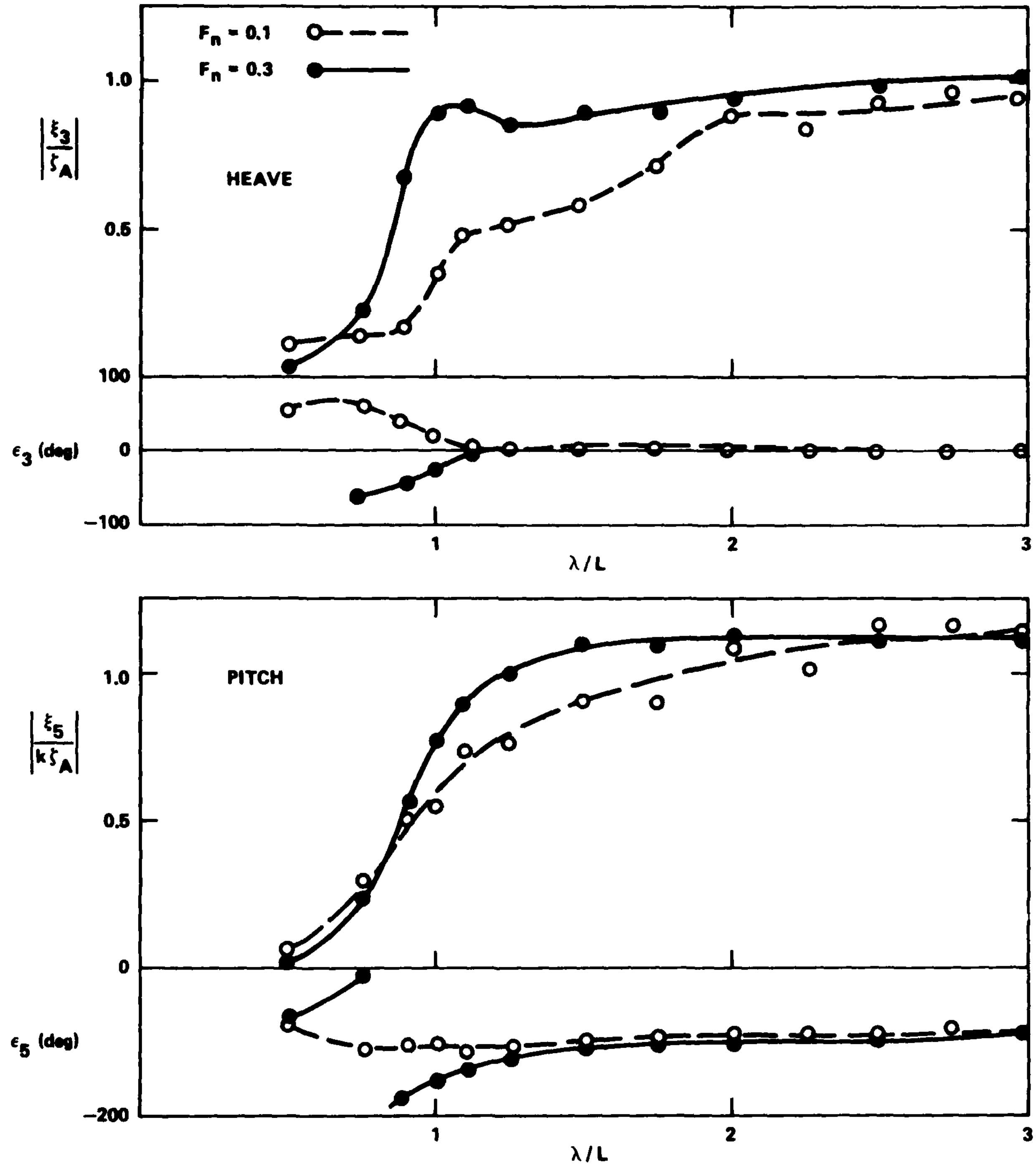


Figure 6 - Measured Heave and Pitch Transfer Functions in Head Waves

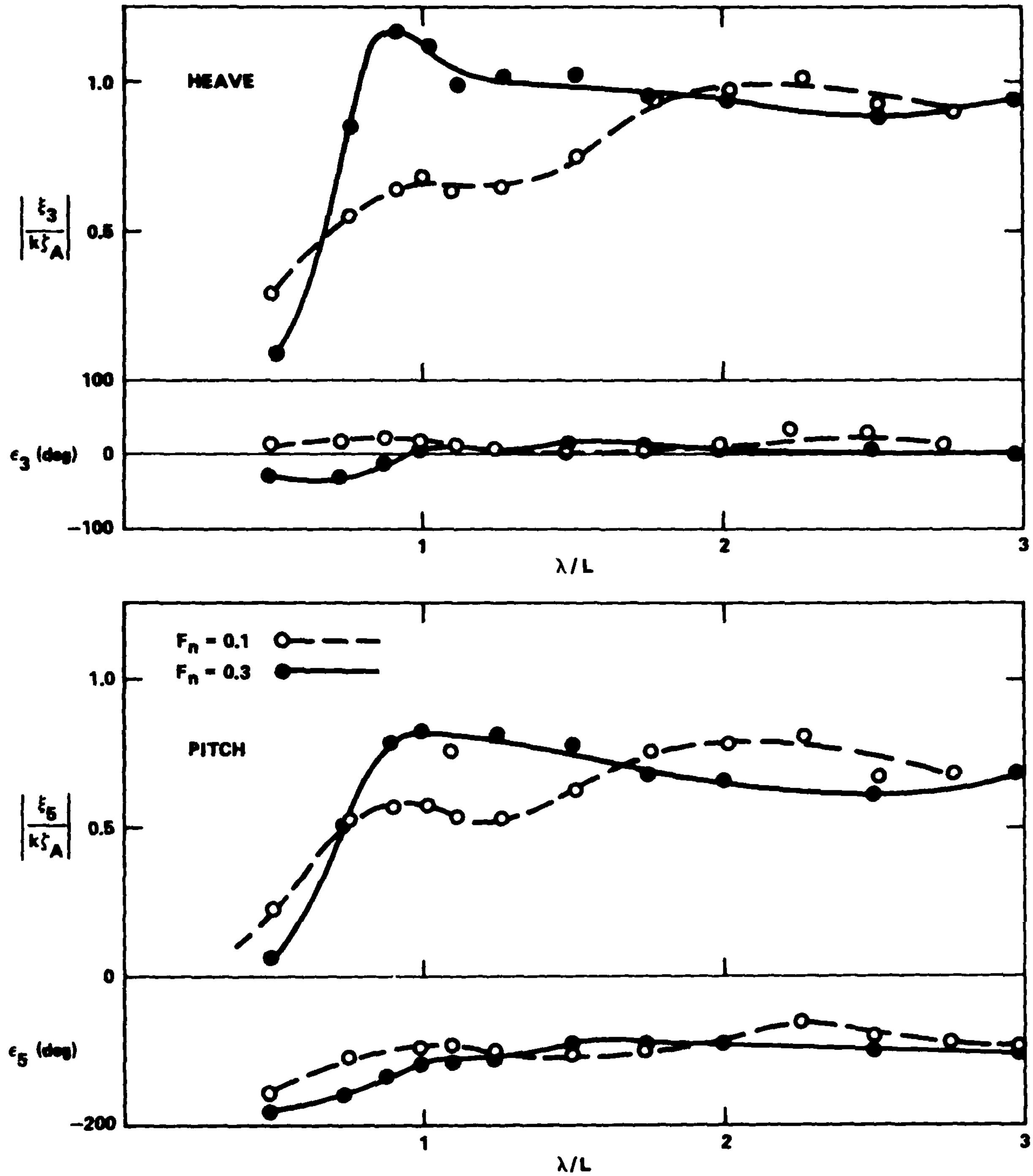


Figure 7 - Measured Heave and Pitch Transfer Functions in Bow Waves

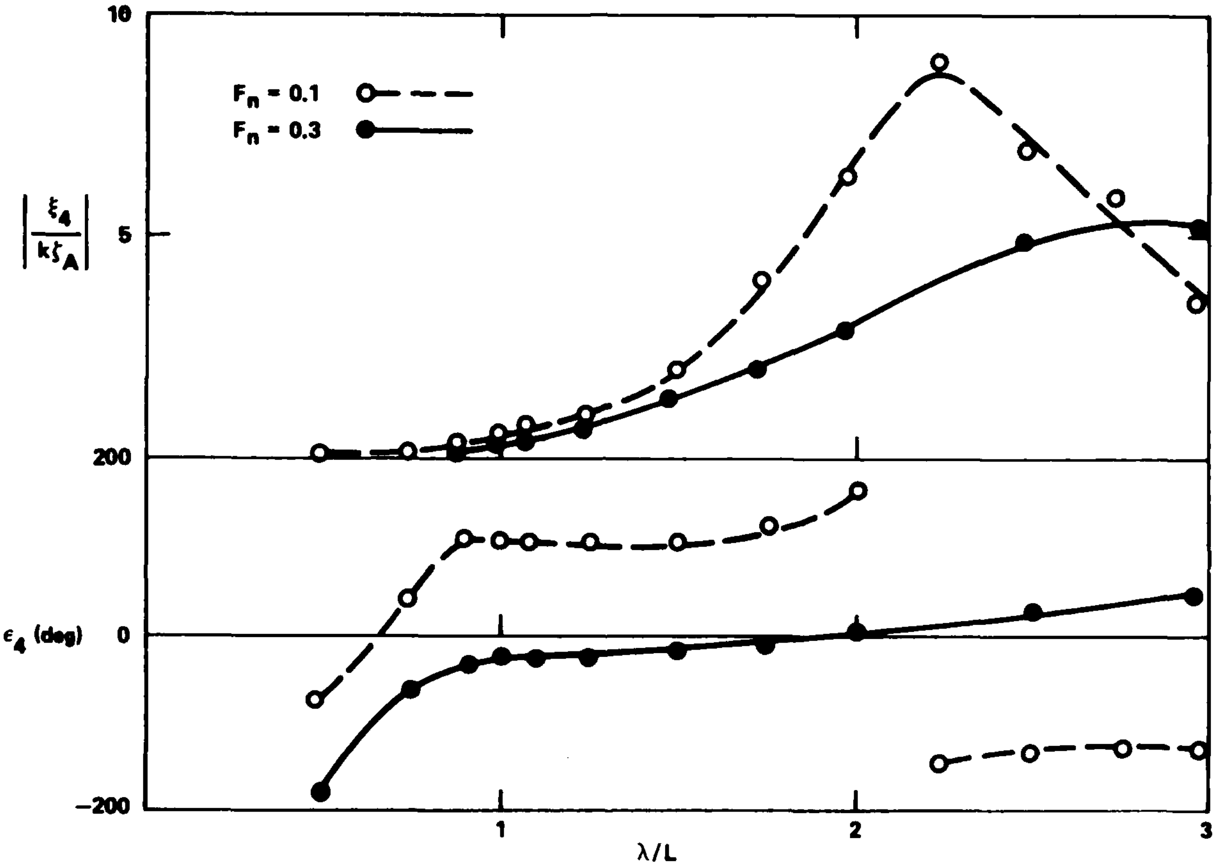


Figure 8 - Measured Roll Transfer Function in Bow Waves

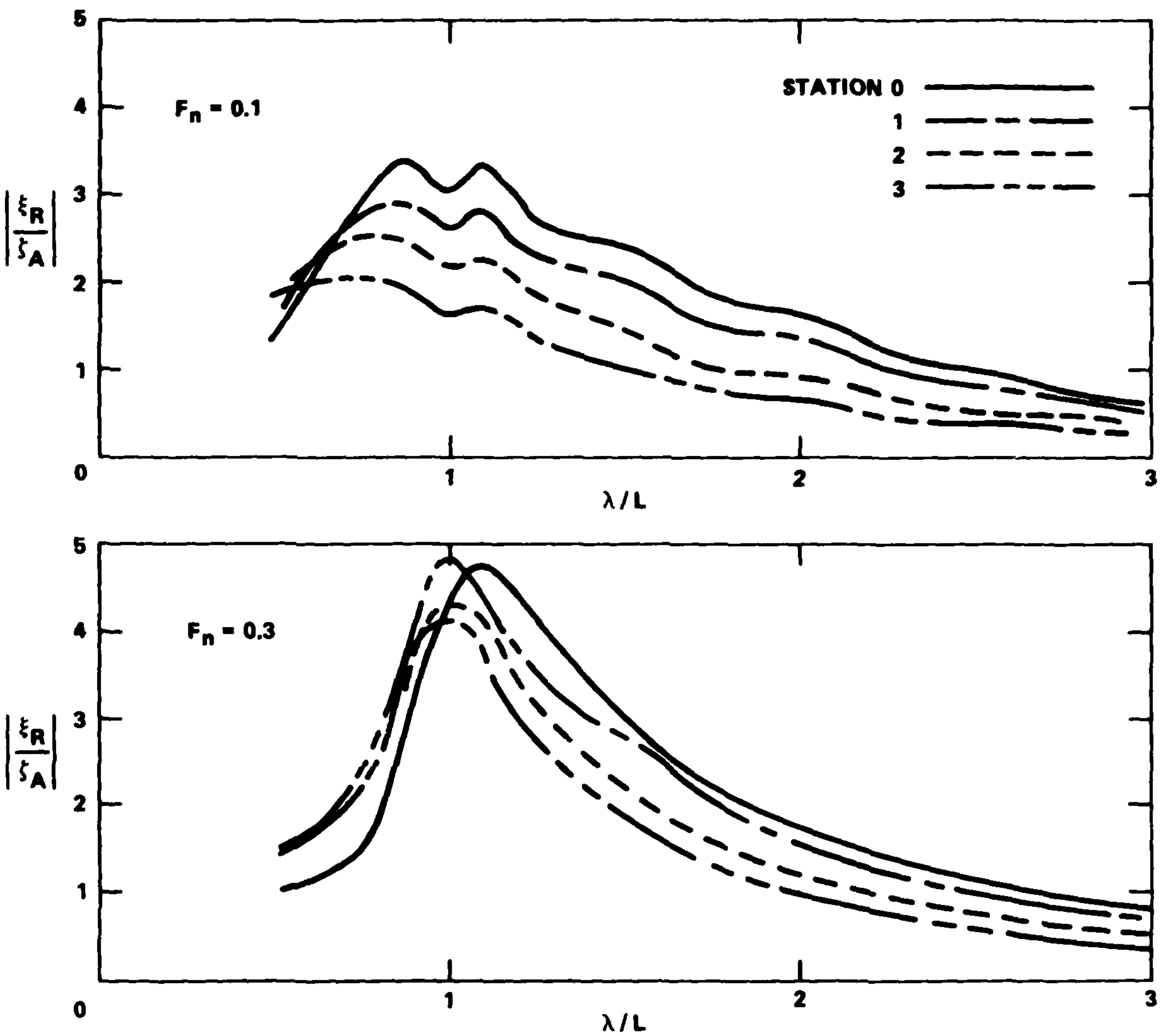
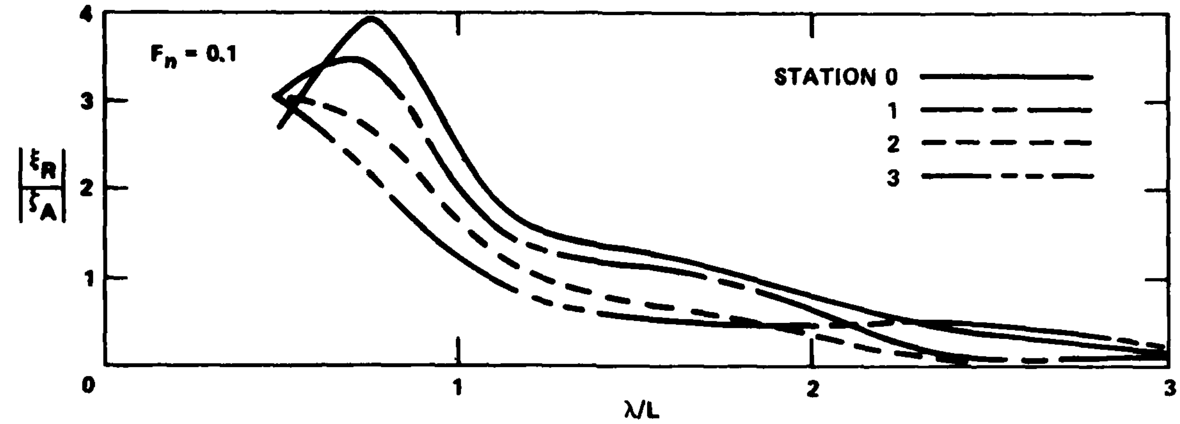


Figure 9 - Measured Magnitude of Relative Motion Transfer Functions in Head Waves



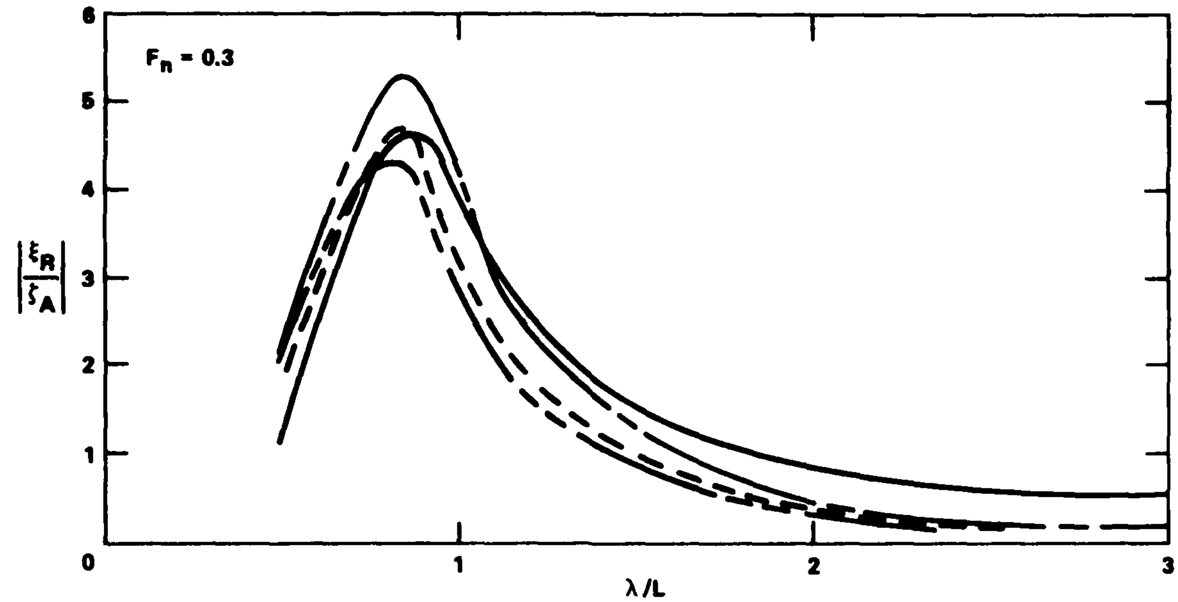


Figure 10 - Measured Magnitude of Relative Motion Transfer Functions in Bow Waves (Weather Side)

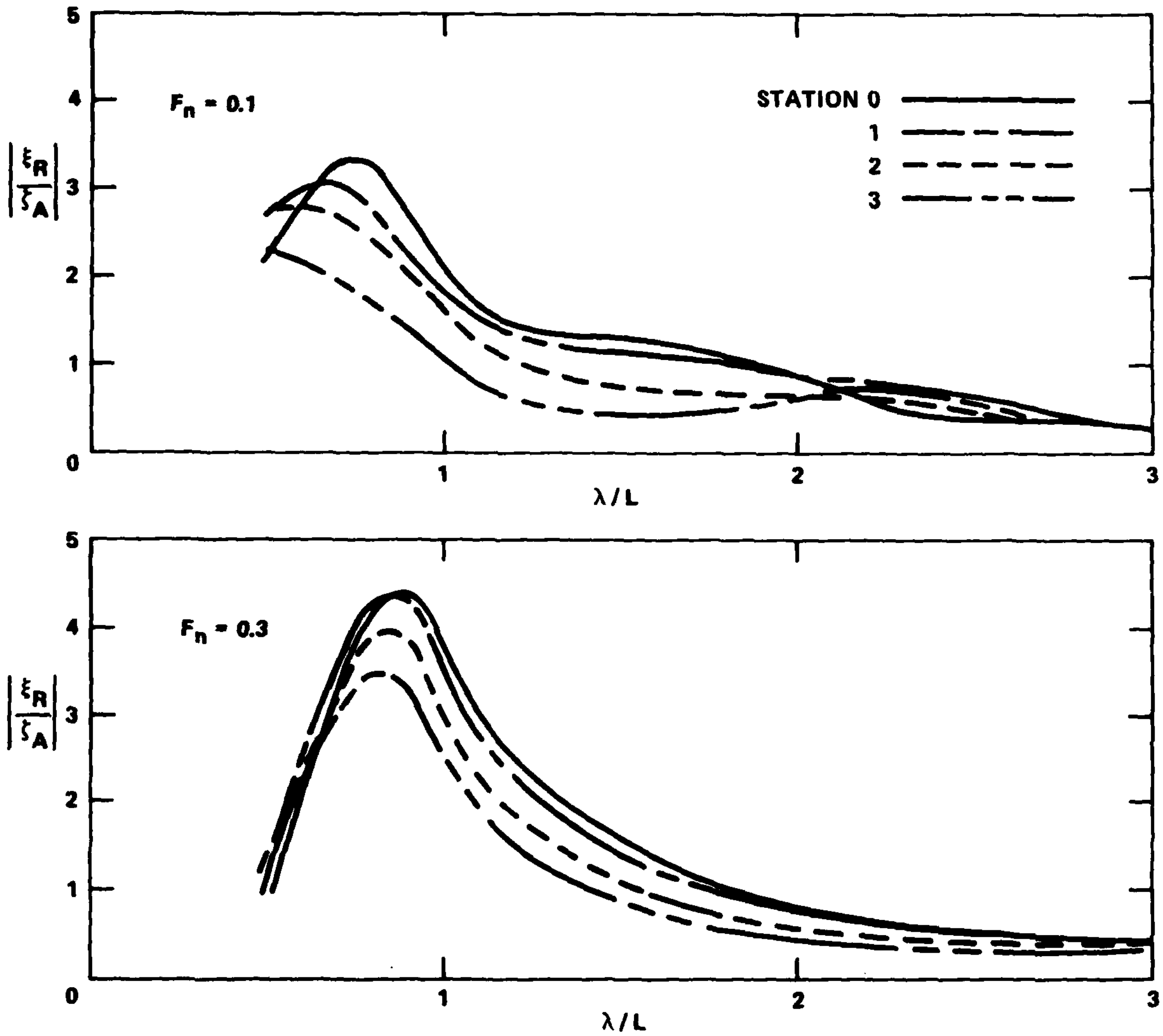


Figure 11 - Measured Magnitude of Relative Motion Transfer Functions in Bow Waves (Lee Side)

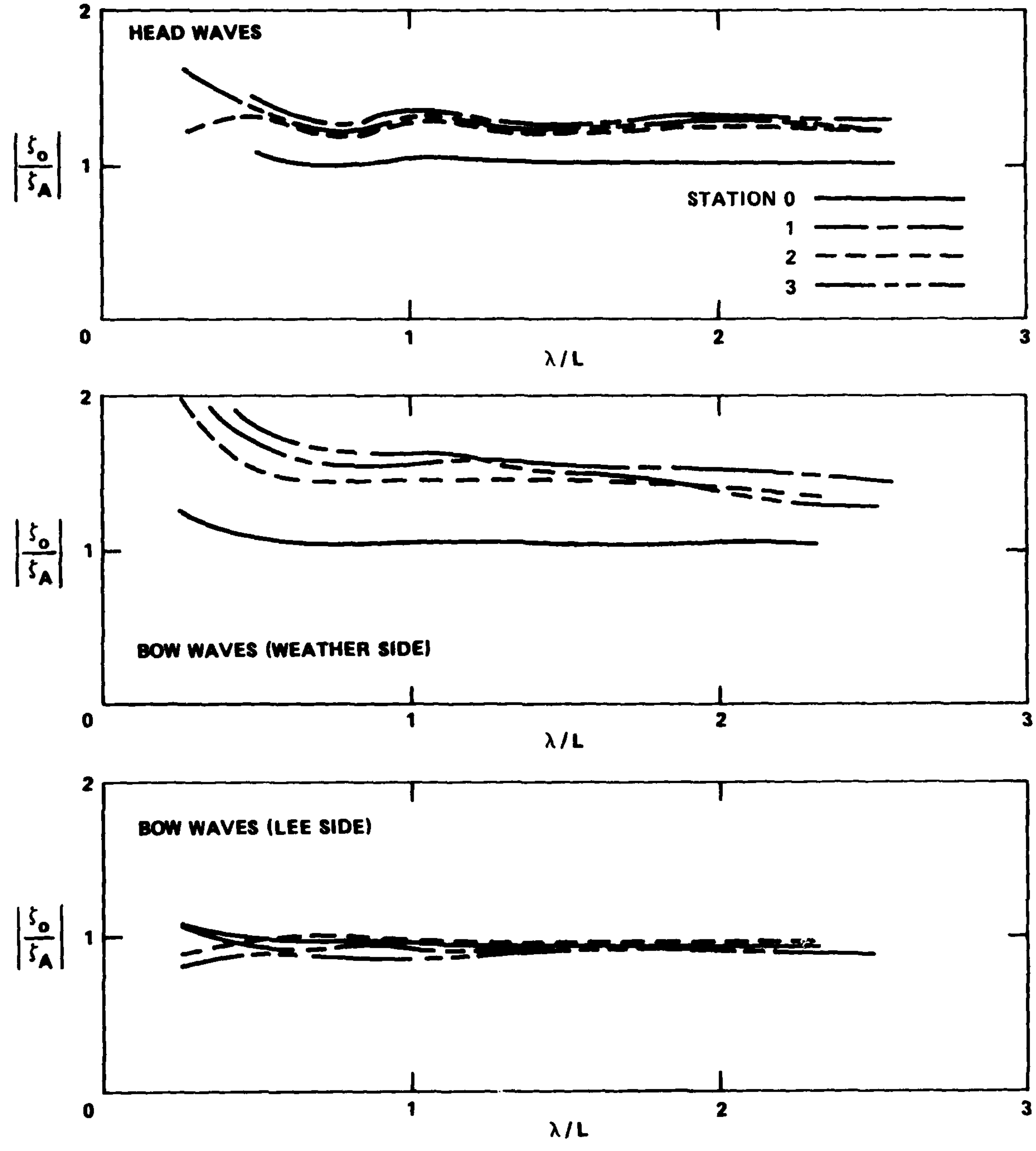


Figure 12 - Effect of Diffraction on Relative Motion at Fn = 0.3

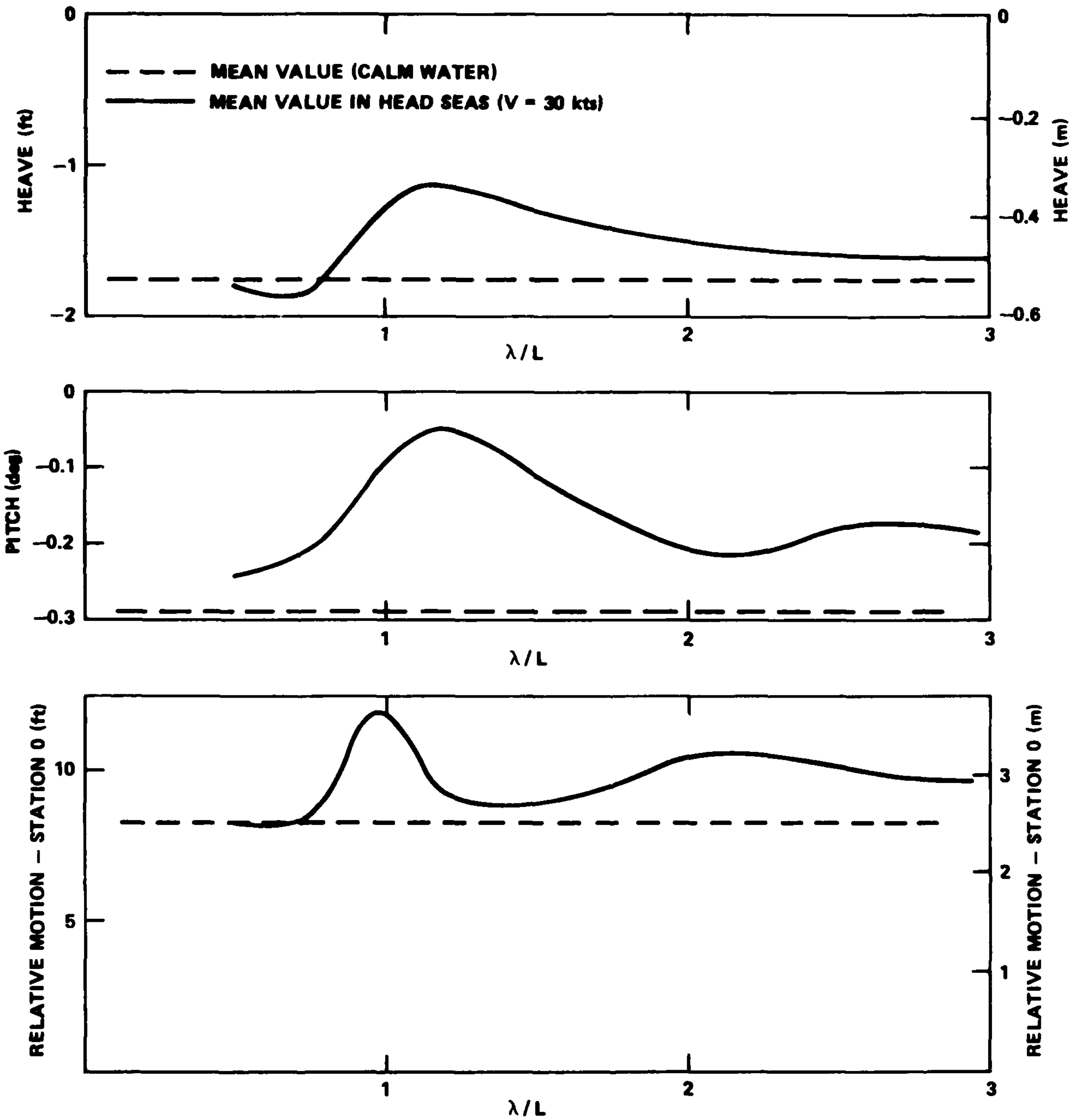
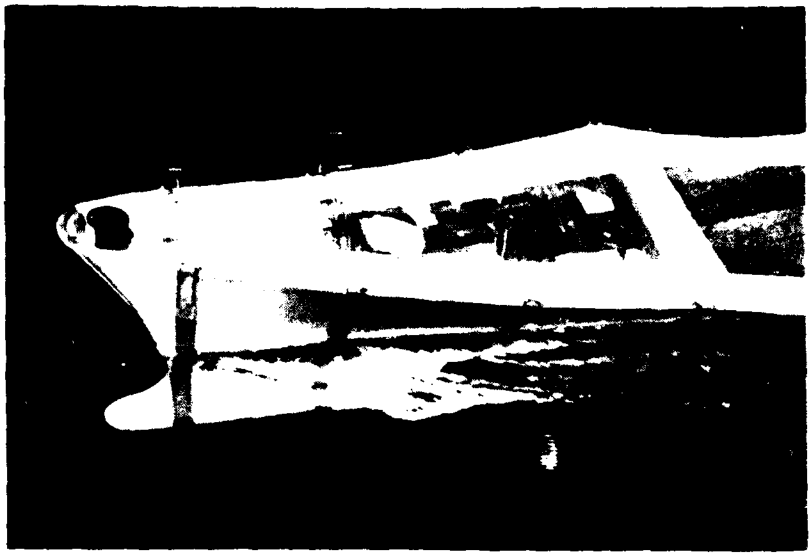
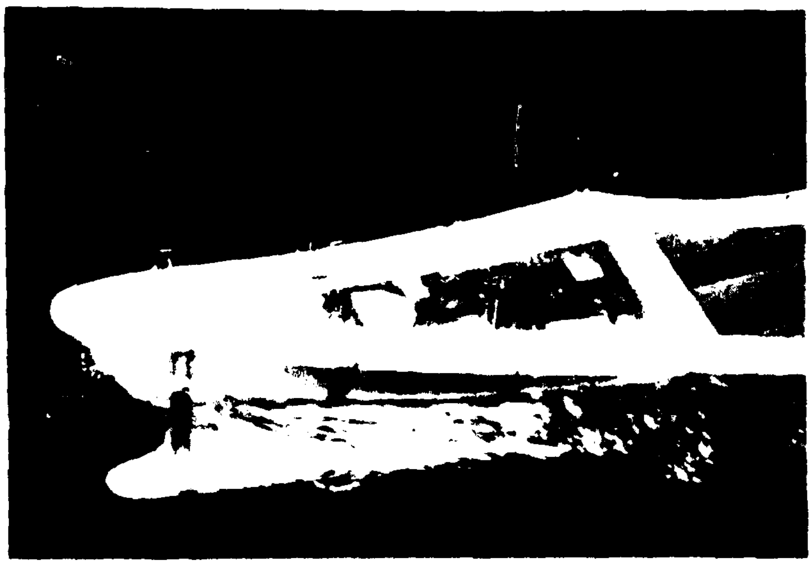


Figure 13 - Shift of Mean Values in Waves

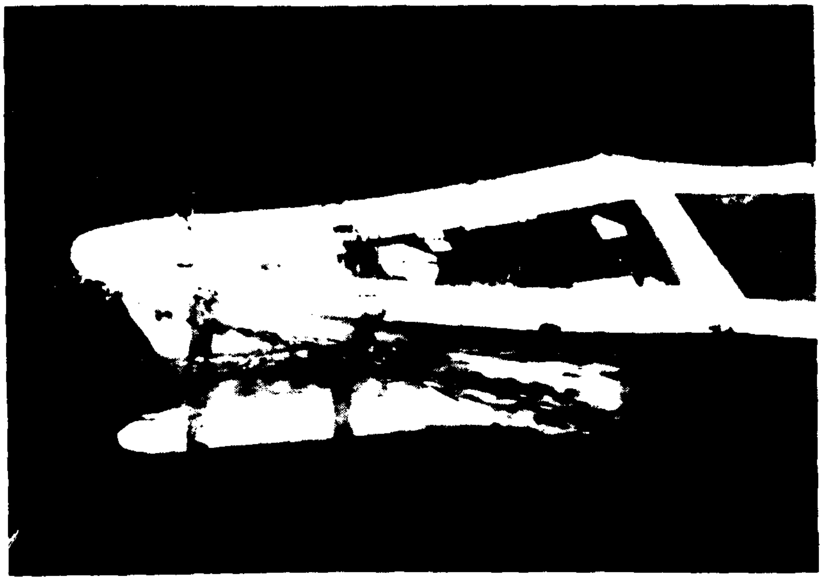


a) V = 10 Knots



b) V = 20 Knots

Figure 14 - Variation of Relative Motion Characteristics with Speed



c) V = 30 Knots

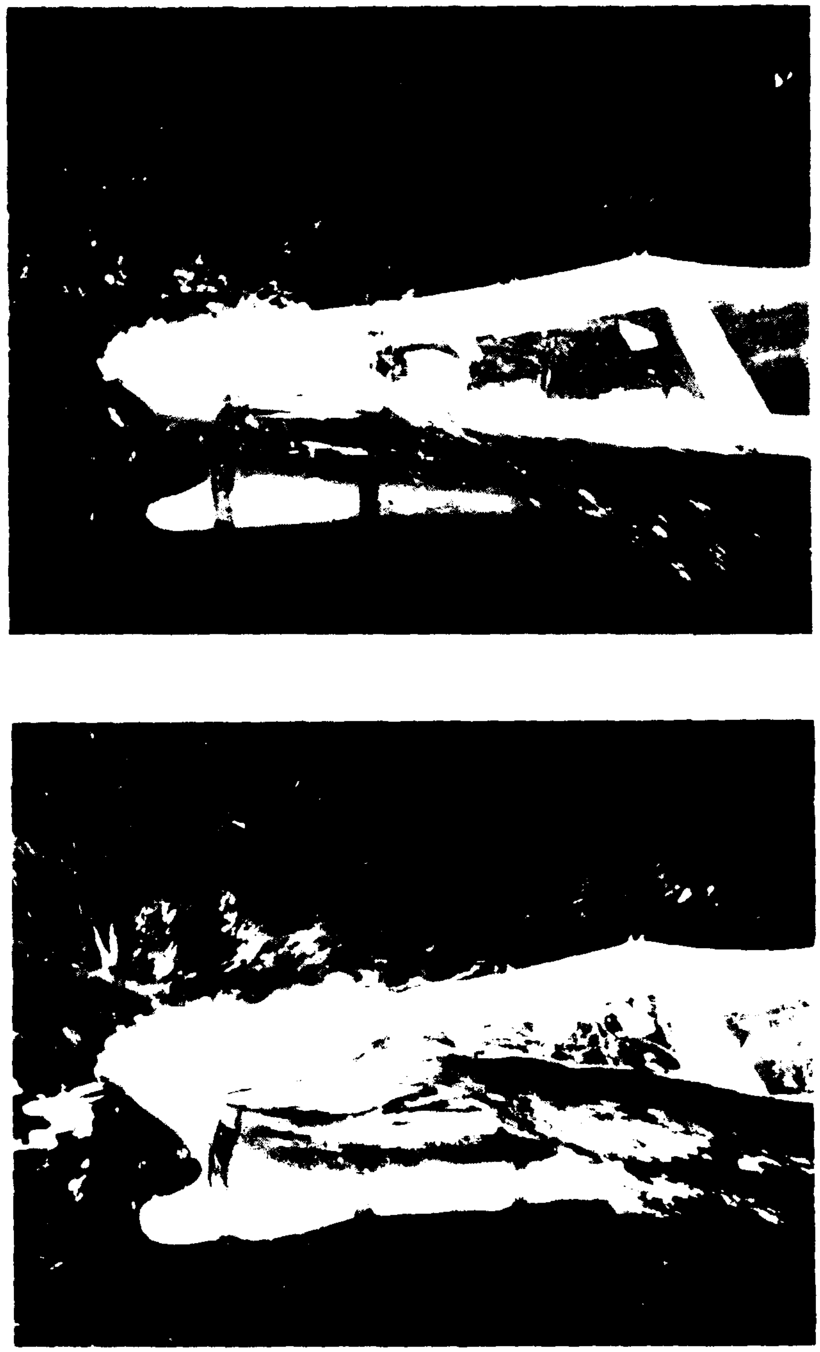


Figure 15 - Relative Motion and Deck Wetness at 30 Knots in Bow Waves, Sea State 7

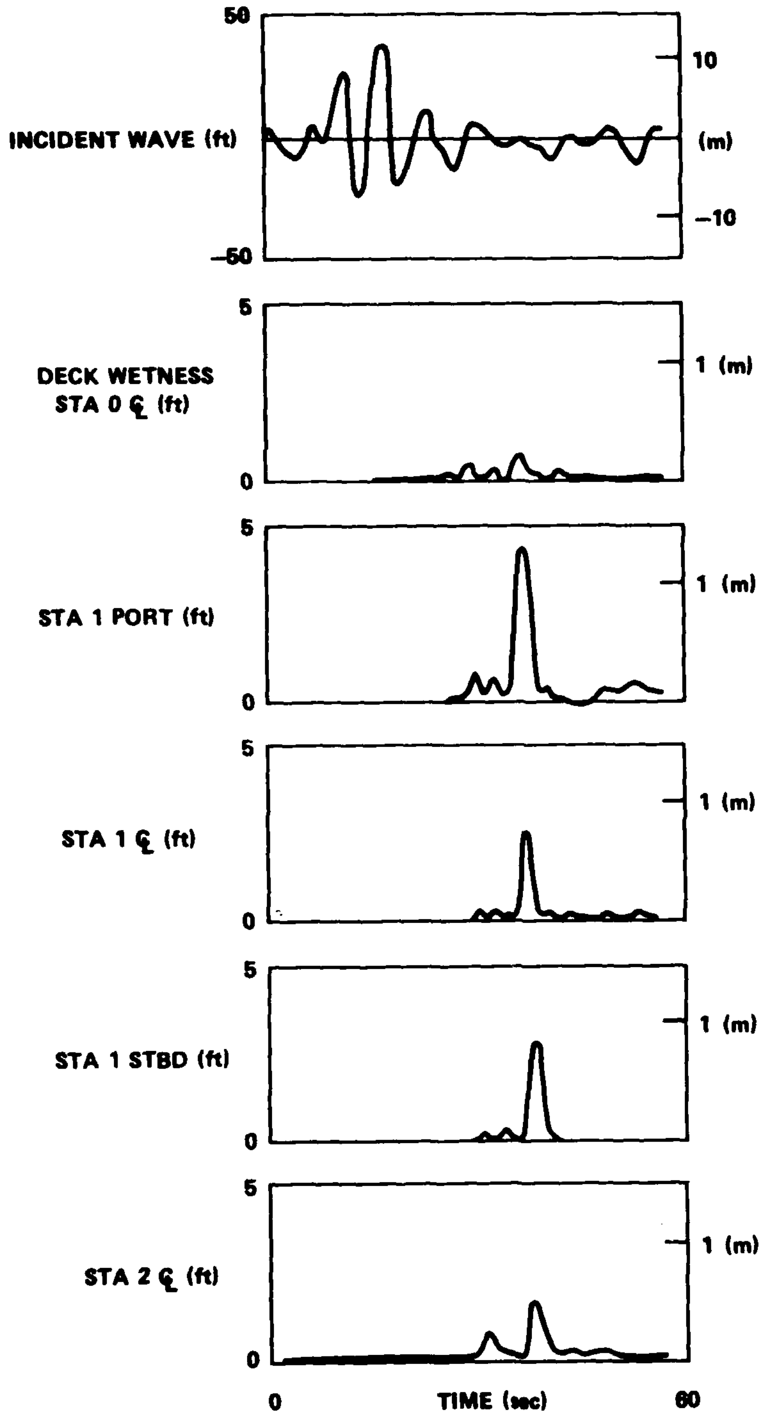


Figure 16 - Occurrence of Water on Deck in Sea State 7 (V = 30 knots, Bow Seas)

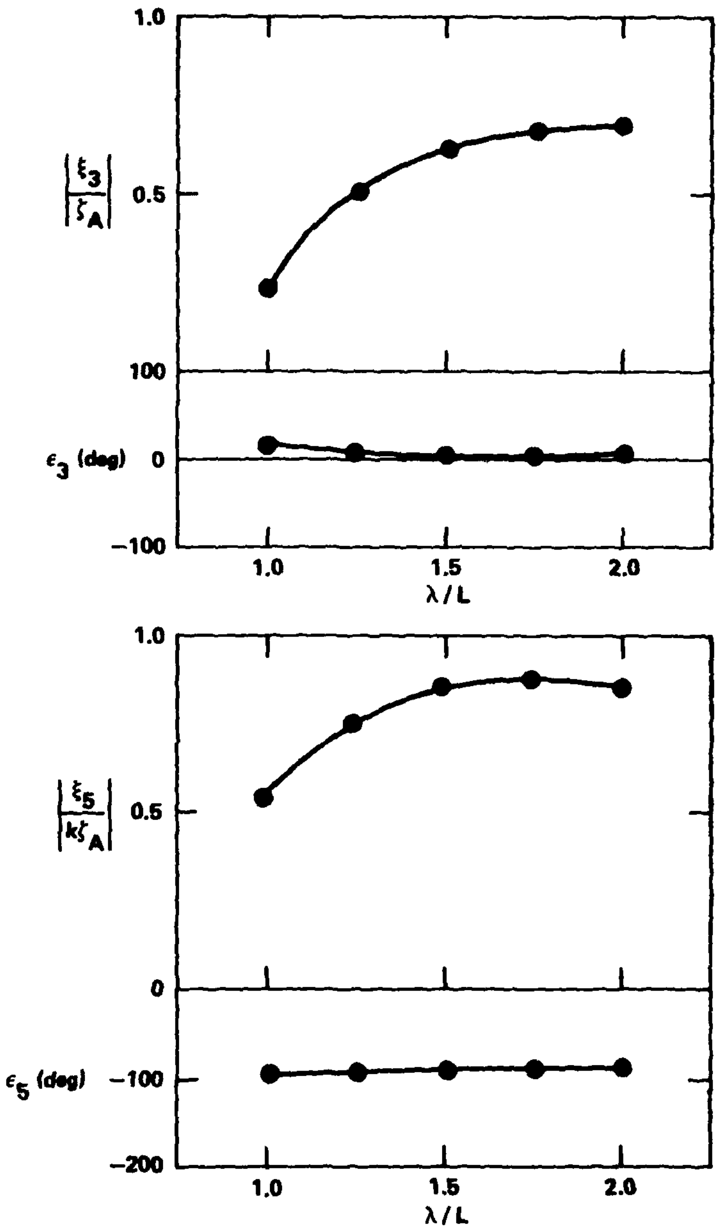


Figure 17 - Pitch and Heave Transfer Functions
in Trimmed Condition

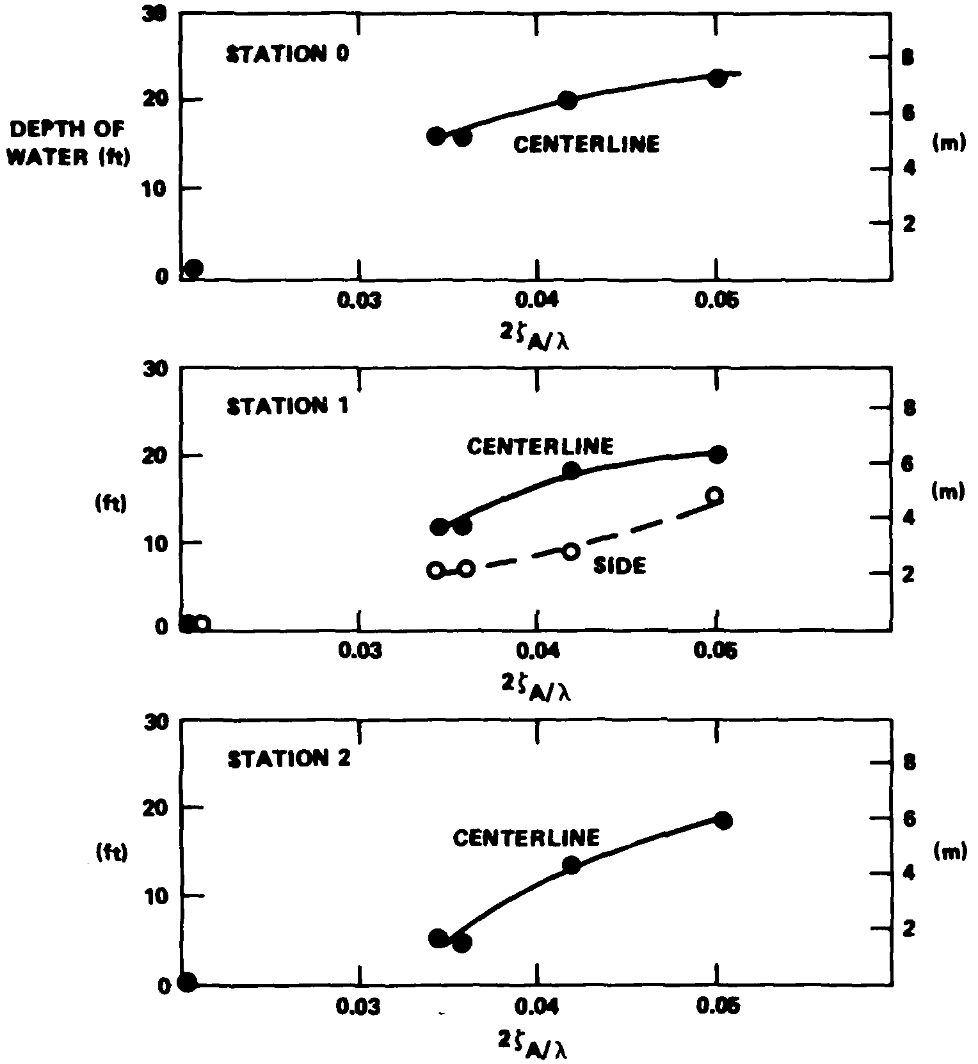


Figure 18 - Depth of Water on Deck in Trimmed Condition
(V = 10 knots, λ/L = 1.5

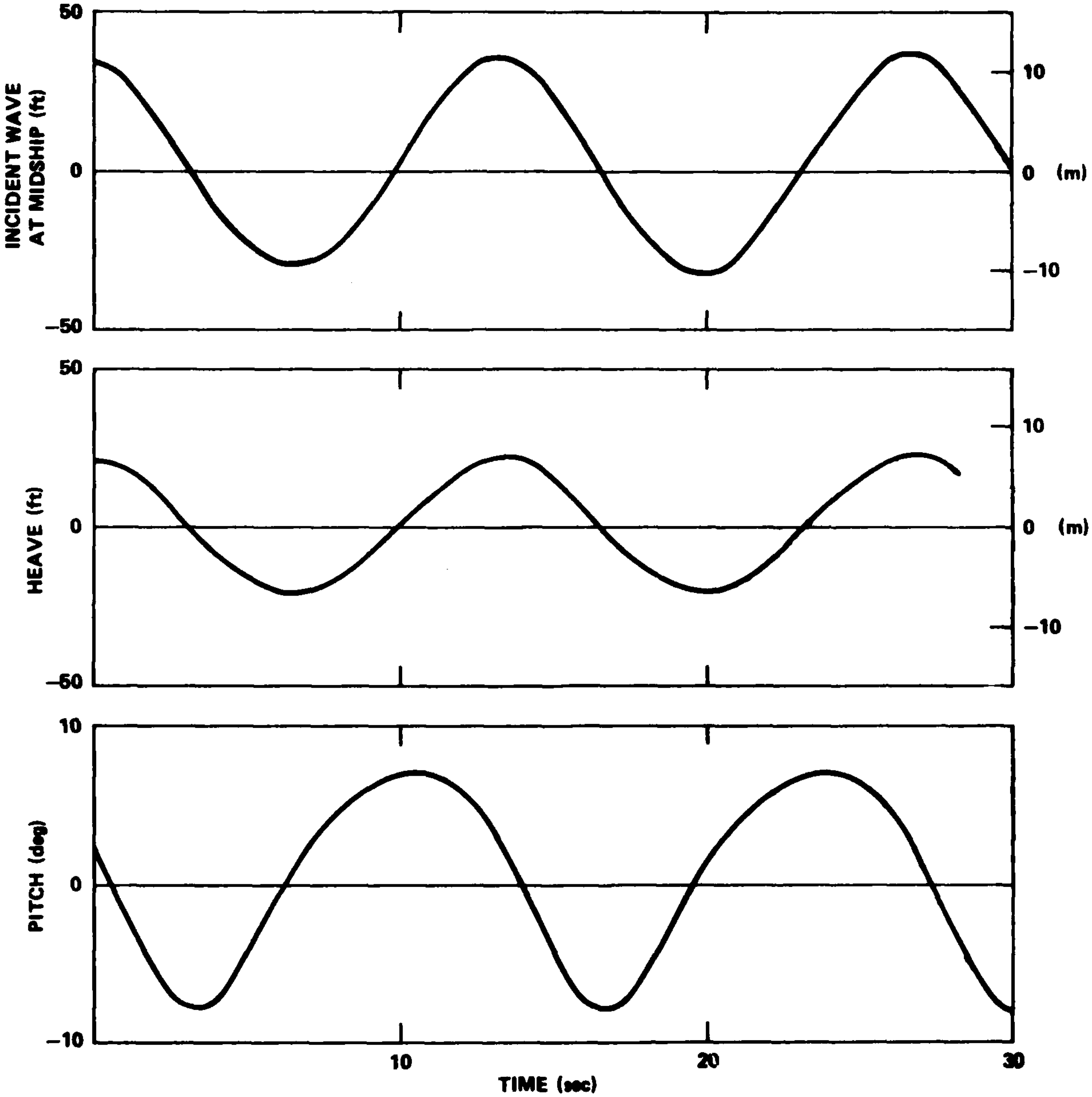


Figure 19 - Time Histories of Absolute Motions in Trimmed Condition
(V = 10 knots, λ/L = 1.5)

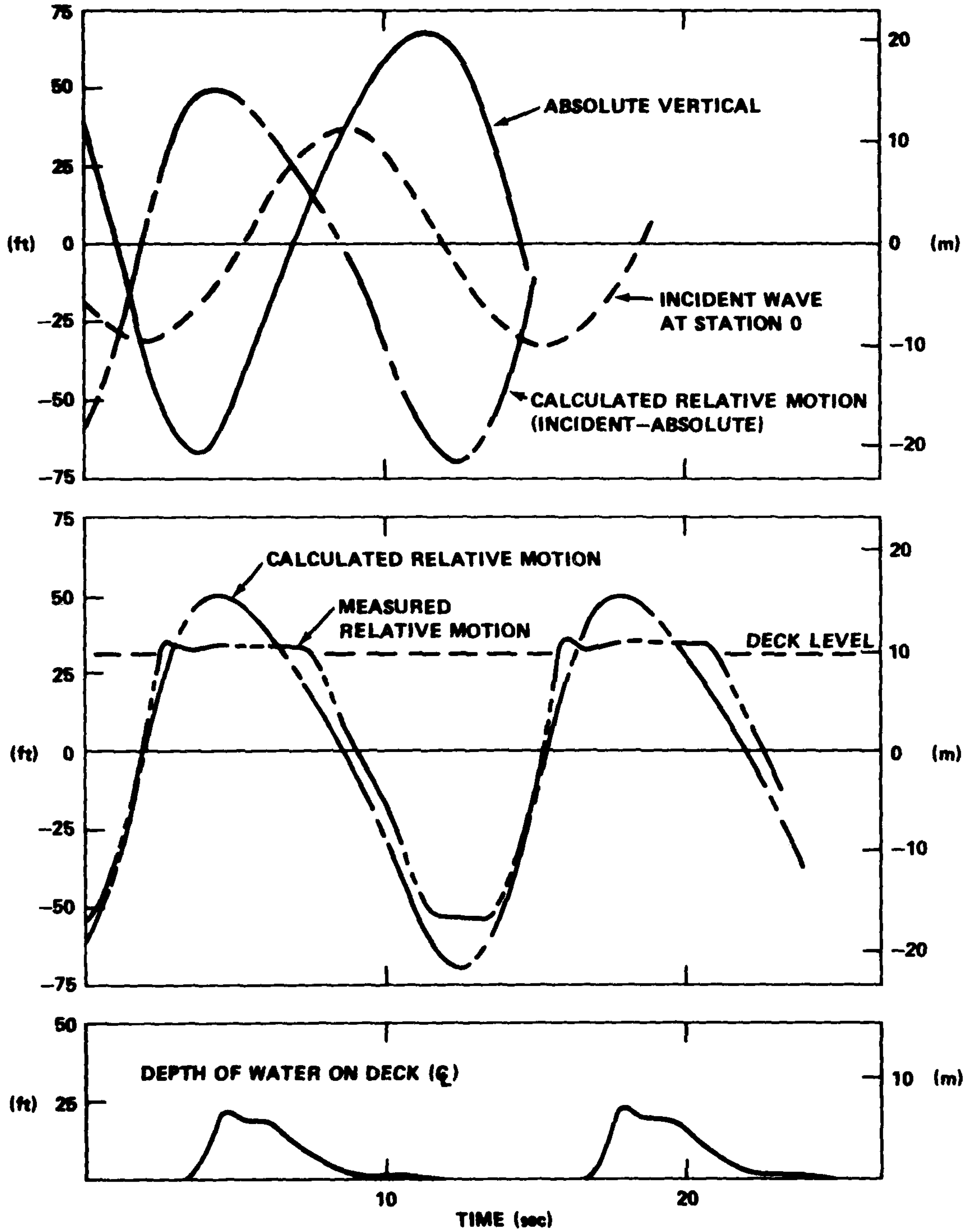


Figure 20 - Time Histories of Relative Motion and Deck Wetness at Station 0 in Trimmed Condition (V = 10 knots, λ/L = 1.5)

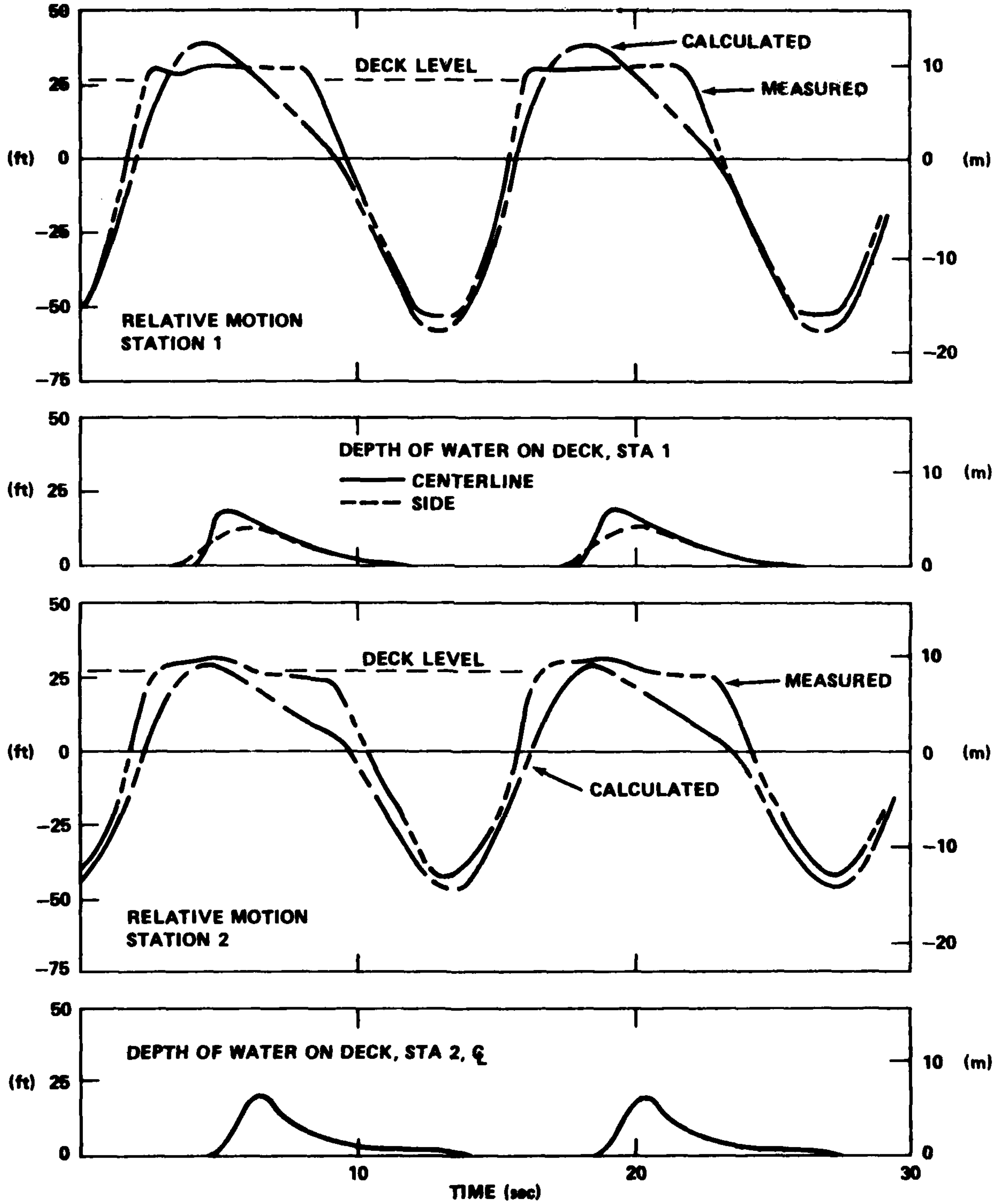


Figure 21 - Time Histories of Relative Motion and Deck Wetness at Stations 1 and 2 in Trimmed Condition (V = 10 knots, λ/L = 1.5)

TABLE 1

PRINCIPAL DIMENSIONS

	FT	(m)
LENGTH (LBP)	880.5	268.4
BEAM	105.5	32.2
DRAFT	34.0	10.4
LCB ($^{LCB}/L$ from FP)	0.528	--
GM_L	4.2	1.3
C_B	0.526	--

TABLE 2

FREQUENCY OF OCCURRENCE OF DECK WETNESS
(OCCURRENCES PER HOUR)

SIGNIFICANT WAVE HEIGHT $(\zeta_\omega)^{1/3}$ (FT)	(M)	HEAD WAVES 10 KNOTS	HEAD WAVES 20 KNOTS	HEAD WAVES 30 KNOTS	BOW WAVES 10 KNOTS	BOW WAVES 20 KNOTS	BOW WAVES 30 KNOTS
10	3.0	0	0	0	0	*	0
15	4.6	0	0	2	*	7	16
25	7.6	3	17	38	*	13	69

* Experiment not done for this condition

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